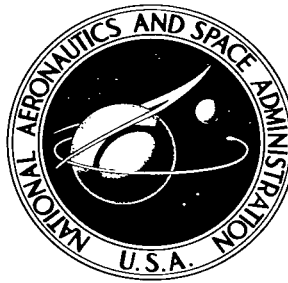


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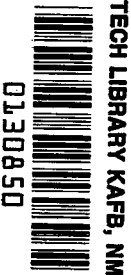


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COMPARISON OF CONVECTIVE STAGNATION HEAT TRANSFER IN AIR, $\text{CO}_2\text{-N}_2$, AND $\text{CO}_2\text{-Ar}$ GAS MIXTURES

by Clifford M. Akin and Joseph G. Marvin
Ames Research Center
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COMPARISON OF CONVECTIVE STAGNATION HEAT TRANSFER

IN AIR, CO₂-N₂, AND CO₂-Ar GAS MIXTURES

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SUMMARY

Convective stagnation-point heat transfer was measured on hemispherical models in air, in 50% CO₂, 50% N₂, and in 65% CO₂, 35% Ar (by volume). The measurements were made in combustion-driven shock tubes over a total enthalpy range from 9.3×10^6 to 48×10^6 J/kg with corresponding stagnation-point pressures from 15 to 160 atmospheres. At the same stagnation enthalpy and pressure, no significant difference was found between the heat transfer measured in air and in the gas mixtures. This observation agrees with theory. The data were adequately predicted by theories which took into account the high stagnation-point pressures of the present tests.

INTRODUCTION

Several experimental investigations have been made of the heating rates in some of the gas mixtures believed to compose the Mars atmosphere (e.g., refs. 1-3). In general, the data from these investigations could be predicted adequately by theory, except for the data from reference 1 for 65% CO₂ and 35% Ar. For stagnation enthalpies from 30×10^6 to 50×10^6 J/kg, these data showed an increase in the heat-transfer parameter not predicted by theory, indicating a need for additional experimental and analytical studies for this gas mixture.

The purpose of the present investigation was twofold: first, to obtain additional experimental stagnation-point convective heat-transfer data in a gas mixture of 65% CO₂ and 35% Ar, and to obtain initial experimental stagnation-point heat-transfer data in a gas mixture of 50% CO₂ and 50% N₂; second, to compare the experimental data from these two gas mixtures with experimental data from the same facilities obtained in air at approximately the same stagnation-point test conditions and to compare each of the test results with theory.

SYMBOLS

a gage thickness

C see equation (A1)

c_p	total specific heat
E	voltage, V
H	total enthalpy, J/kg
I	current, A
K	see equation (2)
M_O	molecular weight, g/mole
N	see equation (A1)
p	pressure, atm
q_w	heat-transfer rate at the wall
R	gage resistance, ohms
R_n	model nose radius
R_O	gage resistance at 0° C, ohms
T	temperature
t	time
u	velocity
α	temperature coefficient of resistance
ρ	density

Subscripts

s	stagnation point
∞	free stream

EXPERIMENTAL PROCEDURE

Facility and Instrumentation

Tests were performed in the Ames 3-inch-diameter combustion-driven shock tube and in the 6.2-inch-diameter driven tube of the Ames 1-foot combustion-driven shock tunnel. The 6.2-inch facility is described in reference 4.

The shock-wave speed and initial pressure of the driven-tube test gas were measured for each test. The shock-wave speed was measured with transducers accurately spaced along the driven-tube wall. These transducers responded with a voltage output, as the shock wave passed, thus giving the time interval between transducers. The initial pressure of the driven-tube test gas was measured with a variety of gages since it varied between 1.0 and 100.0 mm Hg. This pressure range was needed for changing the shock-wave speed, and thus getting the desired range in total enthalpy.

Test Gases

The test gas mixtures used in these experiments were obtained from a commercial supplier. A chemical analysis (by volume) of the gas mixtures was made during the testing phase and is given below.

	N ₂	CO ₂	Ar	Trace Elements
Mixture No. 1		64.1	35.1	0.8
Mixture No. 2	49.6	50.3		.1

Commercially supplied dry air was used as the air test gas.

Model Design

The calorimeter heat-transfer models used in the tests are shown in figure 1 (thick-film calorimeter gages and their application to shock tube

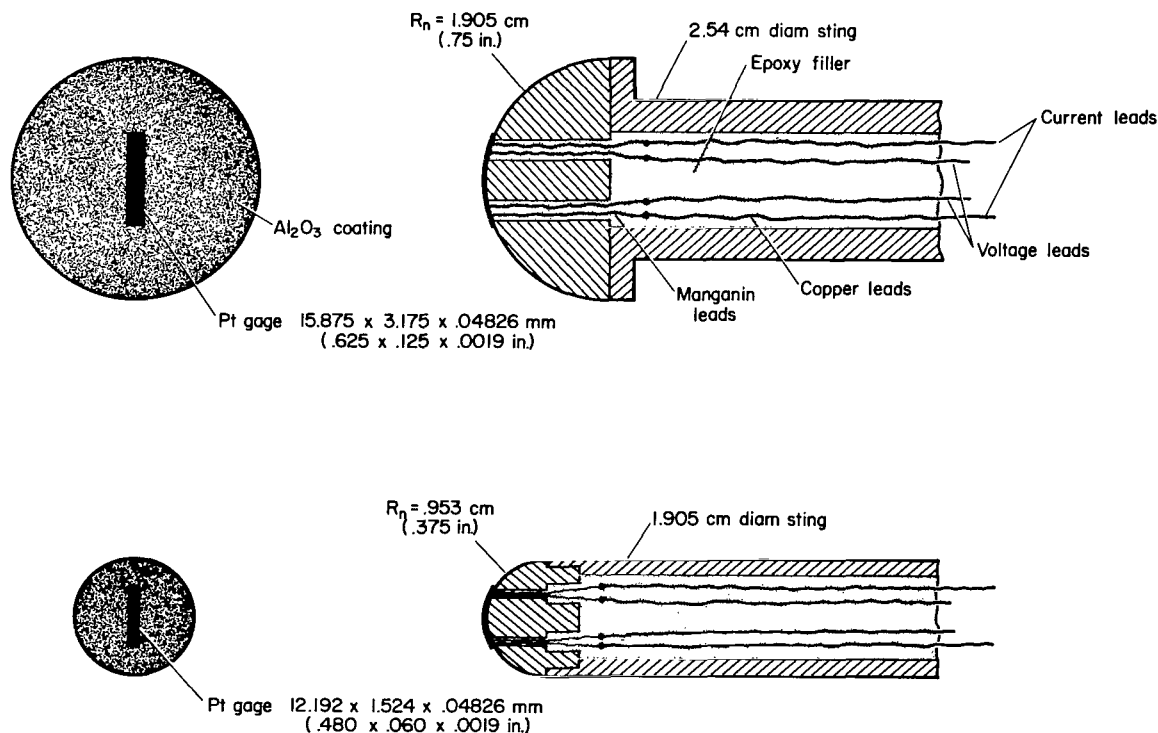


Figure 1.- Models.

testing are discussed in ref. 5). Because of the high heating rates anticipated for these tests, it was concluded that pyrex models, usually used for shock-tube measurements, would be destroyed before usable test data could be obtained. Consequently, the models were made of steel and coated with aluminum oxide for the necessary thermal insulation and electrical isolation for the gage. Four leads were connected to the gage; the inner voltage leads were very thin (to provide a near point contact with the gage) and were spotwelded to the gage to prevent any foreign material from affecting the gage resistance.

The gage was not bonded to the aluminum oxide nor recessed into the model surface.

Gage Calibration

The gage calibration consisted of measuring the $R_0\alpha$ product for each gage-model system. The gage resistance was obtained for three different gage temperatures and plotted versus temperature. The slope of this plot gave $R_0\alpha$ directly, since:

$$R = R_0(1 + \alpha T)$$

and

$$\frac{dR}{dT} = R_0\alpha \quad (1)$$

Measured values of $R_0\alpha$ varied by a maximum of 10 percent from gage to gage.

Gage Instrumentation

The gage circuit and instrumentation are shown in figure 2. The gage voltage drop (across the two inner voltage leads) was measured with an oscilloscope and a differential amplifier. The gage current was measured with a dc ammeter. During the run the current was monitored by measuring the voltage drop across a known resistance in series with the gage (see fig. 2).

Data Reduction

The calorimeter technique described in reference 5 was used for measuring the heat transfer to the platinum gage. Any change in gage temperature (due to heat transfer to the gage) changed the gage resistance and, hence, since the gage current is constant, the gage voltage. Once the change of gage voltage with time is measured, the heat-transfer rate is obtained from:

$$(q_w)_s = K \frac{\rho c_p a}{R_0 \alpha I} \frac{dE}{dt} \quad (2)$$

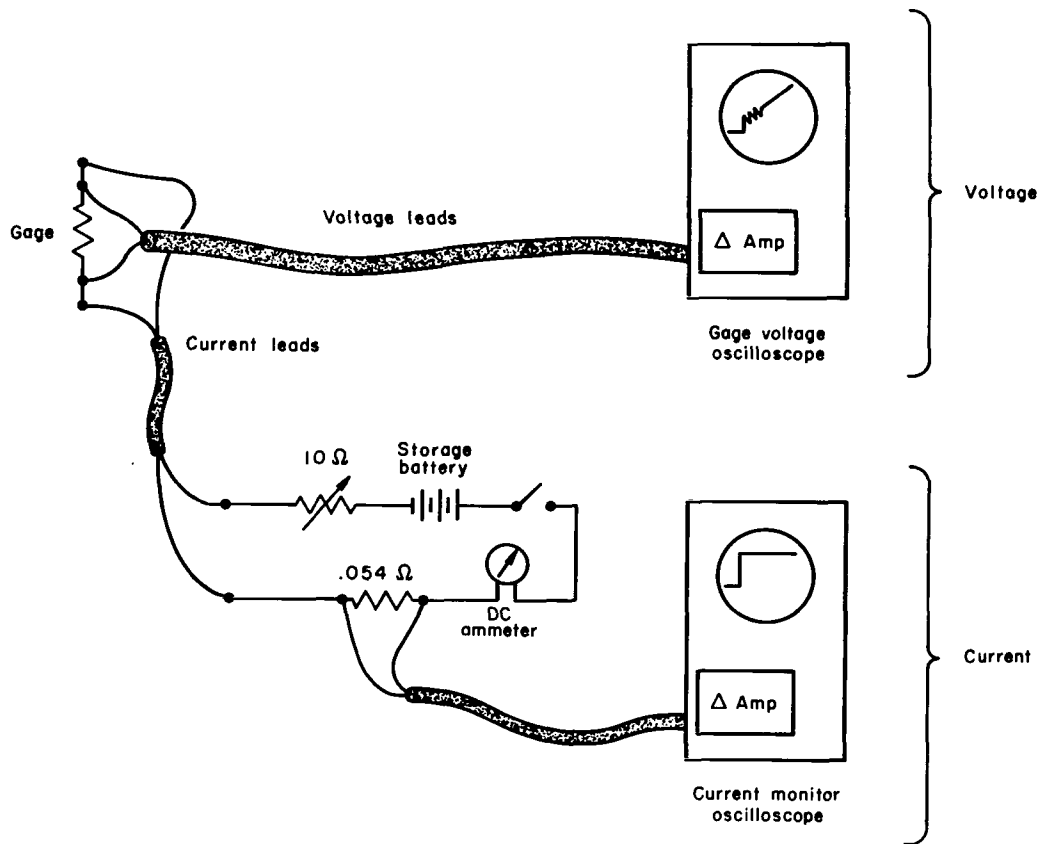


Figure 2.- Gage electrical circuit and instrumentation diagram.

The factor, K , adjusts the average heat-transfer rate measured by the gage to the stagnation-point heat-transfer rate. The change in gage voltage with time, dE/dt , is the slope of the linear portion of the voltage-time trace (fig. 3 is a typical oscillogram). The material properties c_p and ρ were obtained from reference 6. The gage thickness, a , was calculated using ρ and the measured values of gage weight and surface area. The change in gage resistance with temperature, $R_0\alpha$, and the current, I , were obtained from the gage calibration and the dc ammeter reading, respectively.

An estimate of the expected accuracy of the heat-transfer measurement was obtained by estimating the measurement accuracy for each quantity in equation (2), and applying the method described in reference 7. The estimated accuracy was determined to be ± 10 percent of the measured value of $(q_w)_s$. For the gas mixtures, the results of reference 8 were used to calculate representative radiation heat-transfer rates to the gage. The maximum rates, with no self-absorption, were only 6 percent of the measured convective heat-transfer rate. Moreover, self-absorption would considerably reduce the calculated radiation; therefore, no radiation corrections were applied to the data.

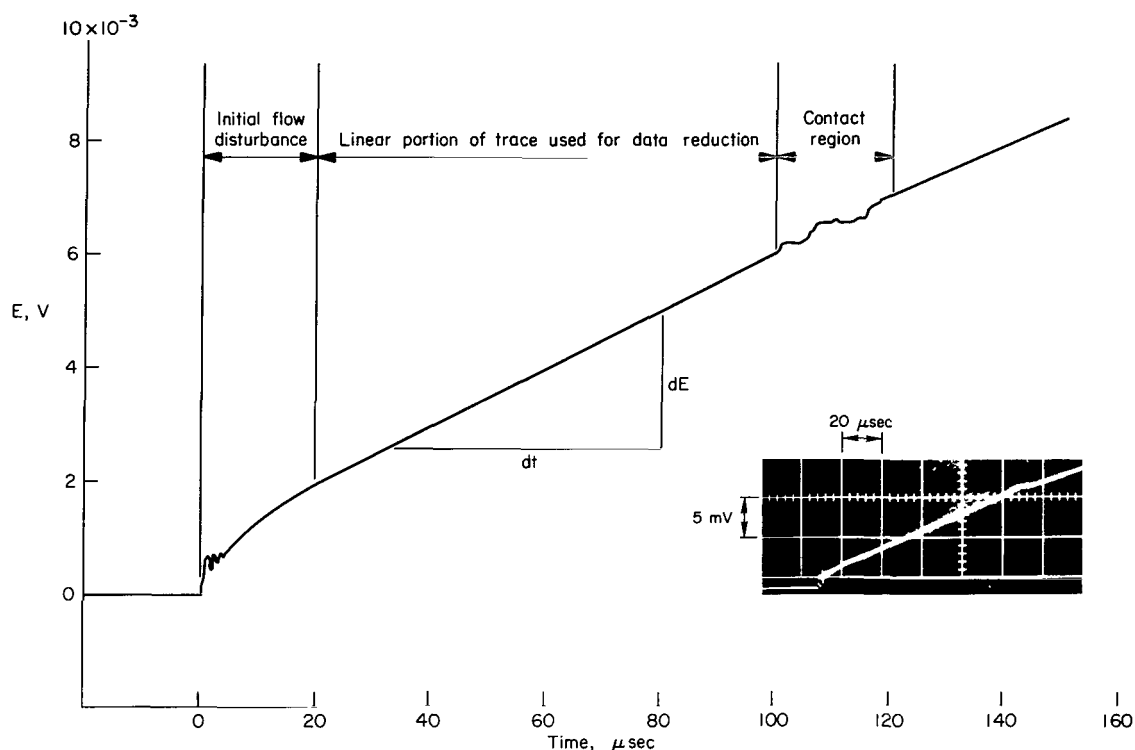


Figure 3.- Typical voltage oscillogram.

The other sources of error investigated were the nonlinear gage temperature distribution and the conduction of heat from the gage to the aluminum oxide backing material. For an average run time of 60 μsec these errors were estimated (by the method of ref. 5) to be 1 and 3 percent of the measured value of $(q_w)_s$, respectively.

The initial pressure and temperature of the driven-tube test gas were used with shock-wave velocity (see ref. 9) to calculate stagnation-point enthalpy, density, pressure, and temperature. The thermodynamic properties of each test gas were computed separately by the method described in reference 10. The stagnation-point thermodynamic properties were compared at several initial pressures and shock speeds and were found to agree with those properties given in reference 1 for the 65% CO_2 , 35% Ar mixture, and in reference 9 for air.

RESULTS AND DISCUSSION

Measurements of convective stagnation-point heat transfer in air, in 50% CO_2 , 50% N_2 , and in 65% CO_2 -35% Ar (by volume) are presented in this section and are compared with other data and several theories. Since the stagnation-pressure level was different for all the tests, the data are presented in the form of the familiar heat-transfer parameter $(q_w)_s \sqrt{R_n/p_s}$, which eliminates

the major effects of stagnation-point pressure level. For the present tests the highest stagnation-point pressure corresponds to the lowest stagnation-point enthalpy.

Heat-transfer tests were performed first in air to provide a basis of comparison for the heat-transfer data obtained in the gas mixtures and also to verify the present test techniques. The results are presented in figure 4

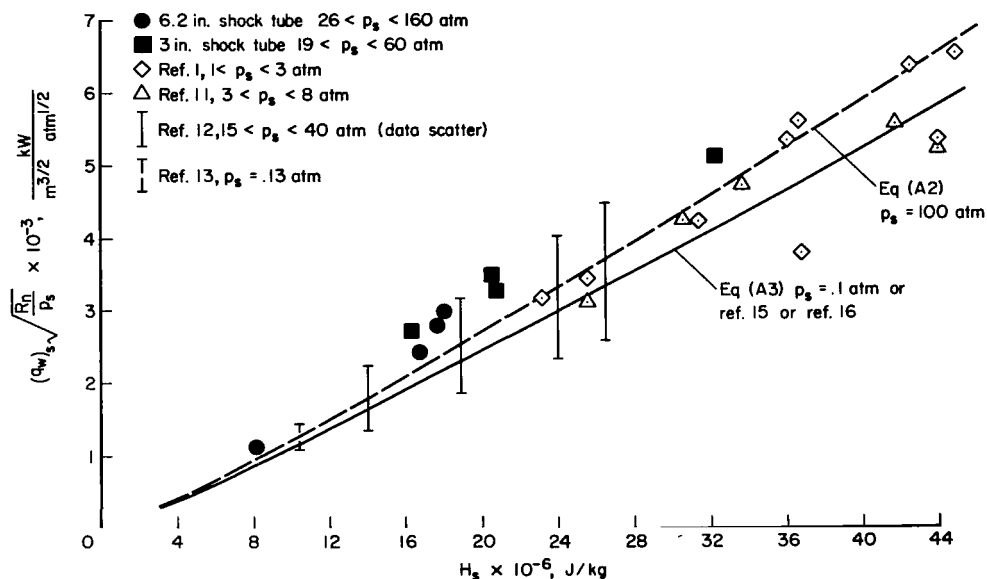


Figure 4.- Stagnation-point heat transfer for air.

where the heat-transfer parameter is plotted as a function of total enthalpy. Data from both the 3-inch and 6.2-inch facilities are given (solid symbols). No significant differences were found between the sets of data from the two facilities. Representative experimental data from several other sources (refs. 11, 12, and 13) are also shown. The present data lie along the upper level of these other data because the present stagnation-pressure conditions are consistently higher (the heat-transfer parameter is not entirely independent of pressure as will be shown) and because test techniques and facilities differ.

To demonstrate the dependence of the heat-transfer parameter on p_s , correlation equations of this parameter as a function of u_∞ and M_0 were obtained by curve fitting the numerical solutions for the various gas mixtures studied in reference 14 for $p_s = 100$ and 0.1 atmosphere, respectively, see appendix A. These two equations are plotted in figure 4. The predicted difference in the heat-transfer parameter for this change in pressure is about 10 percent with the higher prediction corresponding to the higher pressure. The prediction for $p_s = 0.1$ atmosphere agrees with that predicted by equation (9) from reference 15 (obtained by approximating numerical calculations of the heat transfer for stagnation pressure between 0.001 and 10 atmospheres by a single equation accurate to within ± 16 percent), and with the theory of reference 16.

The present data are about 15 percent higher than predicted for $p_s = 100$ atm, but the agreement between experiment and theory is considered adequate.

The heat-transfer parameter for 50% CO_2 , 50% N_2 is given as a function of total enthalpy in figure 5. The data are compared with theoretical values

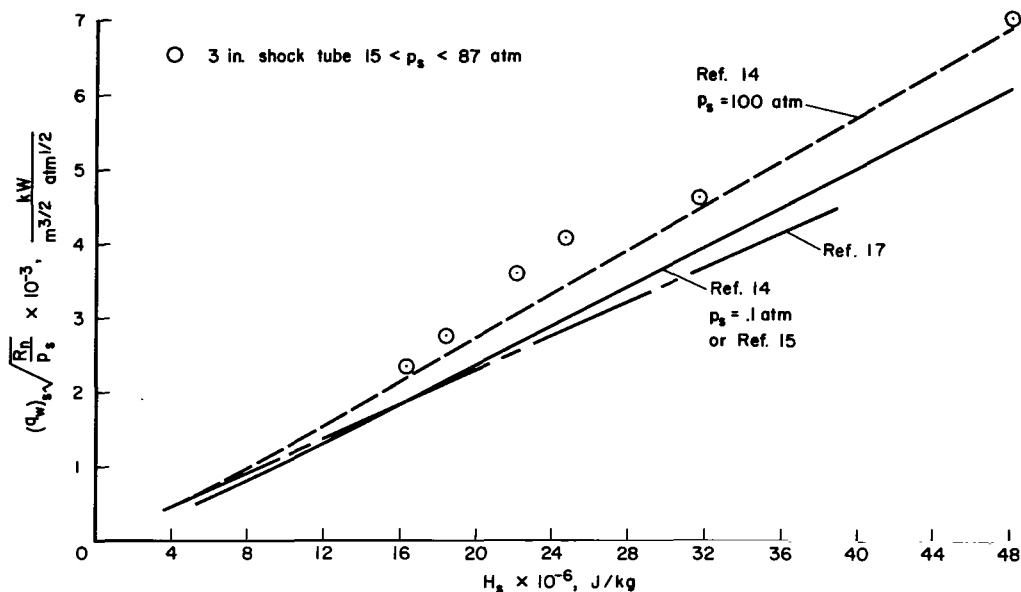


Figure 5.- Stagnation-point heat transfer for 50% CO_2 -50% N_2 .

from three sources. The theoretical predictions from reference 14 for a gas mixture of 39% CO_2 , 61% N_2 (by volume) are shown for $p_s = 100$ atm, and $p_s = 0.1$ atm. The difference between these predictions represents the dependence of the heat-transfer parameter on pressure level. Also, these predictions agree with those of equations (A2) and (A3), indicating that the small differences in composition have no effect on the predicted heat transfer. The prediction for $p_s = 0.1$ atm agrees with the previously described correlation equation from reference 15. Also shown are values obtained from equation (56) given in reference 17. This correlation equation was derived from analytical solutions assuming constant free-stream pressure and hence variable stagnation pressure. The data, obtained for $15 < p_s < 87$ atm, agree reasonably well with that predicted for $p_s = 100$ atm, thus indicating that the heat-transfer parameter can be adequately predicted by the theory for the appropriate stagnation-point pressure.

The heat-transfer parameter for 65% CO_2 , 35% Ar is plotted as a function of total enthalpy in figure 6, along with the data from reference 1. The two sets of data agree reasonably well up to enthalpies of 30×10^6 J/kg; beyond this value the data from reference 1 show an increase with enthalpy, not evident in the present data. The theoretical prediction for this gas mixture taken from reference 18 for $p_s = 100$ atm agrees with the present data for $30 < p_s < 70$ atm. Also presented are the previously described correlation equations from references 15 and 17, which represent a lower stagnation-point pressure (i.e., $p_s \approx 0.1$ atm).

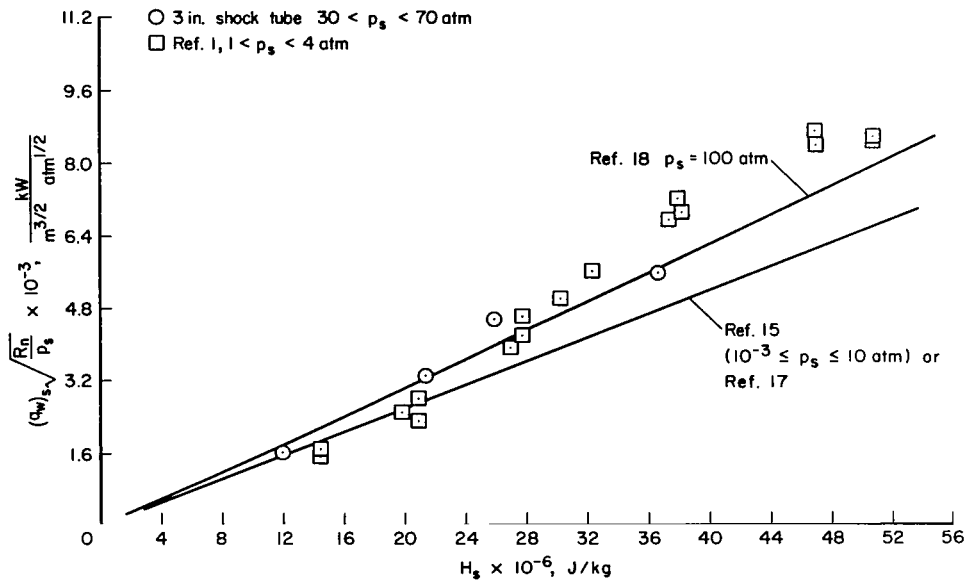


Figure 6.- Stagnation-point heat transfer for 65% CO₂-35% air.

It is informative to compare the data obtained in the two gas mixtures with those obtained in air (fig. 7). The heat-transfer parameters obtained in

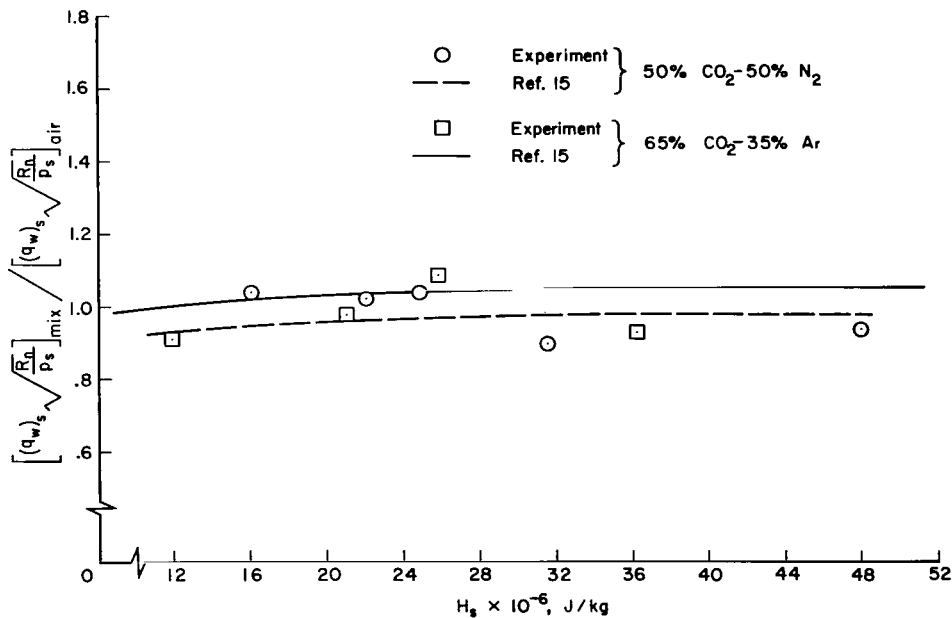


Figure 7.- Experimental and theoretical comparison of the stagnation-point heat transfer of gas mixtures with air.

50% CO₂, 50% N₂, and in 65% CO₂, 35% Ar for various enthalpies are shown as ratios to air values at corresponding enthalpies, obtained by fairing a curve through the experimental air data. The data ratios scatter between 0.9 and

1.1, with no particular trend. Also shown are the theoretical trends expected for this ratio from the theory of reference 15. The theory predicts ratios between 0.92 and 0.99 for 50% CO₂, 50% N₂ and 1.0 to 1.06 for 65% CO₂, 35% Ar. Within the expected range of accuracy it is concluded that the present data show no significant difference between the heat-transfer parameters for air and the gas mixtures when compared at the same stagnation enthalpy. This observation agrees with theory.

CONCLUSIONS

Shock-tube stagnation-point heat-transfer measurements in air, in 50% CO₂, 50% N₂, and in 65% CO₂, 35% Ar over an enthalpy range from 9.3×10^6 to 48×10^6 J/kg (equivalent flight speeds of 4.6 to 10.3 km/sec) resulted in the following conclusions:

1. No significant difference in the convective stagnation-point heat-transfer parameter was found between air, 50% CO₂, 50% N₂, and 65% CO₂, 35% Ar, when compared at the same stagnation enthalpy. This agrees with theoretical predictions.

2. The present data are within 15% of theoretical predictions which take into account the high stagnation pressure level of the present data.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., 94035, Sept. 8, 1967
129-01-09-07-00-21

APPENDIX A

CORRELATION EQUATIONS

Theoretically computed values of the stagnation-point heat transfer for a range of total enthalpy and pressure, for CO₂ and three CO₂-N₂ gas mixtures, are given in reference 14. These computed values, for stagnation pressures of 100 and 0.1 atmosphere, were used to approximate an equation of the form:

$$(q_w)_s \sqrt{\frac{R_n}{p_s}} = C \left(\frac{u_\infty}{10^4} \right)^N \quad (A1)$$

The results are shown in this table:

Gas-gas mixture (by mass)	p _s , atm	C	N	Enthalpy range, J/kg
100% CO ₂	100 0.1	104.5 86	2.0 2.1	11.6×10 ⁶ - 47.0×10 ⁶
90% CO ₂ -10% N ₂	100 0.1	104 85.5	2.03 2.13	11.6×10 ⁶ - 58.0×10 ⁶
50% CO ₂ -50% N ₂	100 0.1	88.5 74	2.13 2.23	11.6×10 ⁶ - 47.0×10 ⁶
10% CO ₂ -90% N ₂	100 0.1	83 67	2.2 2.3	11.6×10 ⁶ - 51.0×10 ⁶

For each stagnation-point pressure the values of C and N for the CO₂ and the gas mixtures were correlated on the basis of their respective molecular weights. The resulting equations are:

p_s = 100 atm:

$$(q_w)_s \sqrt{\frac{R_n}{p_s}} = (34 + 1.6M_o) \left(\frac{u_\infty}{10^4} \right)^{2.57 - 0.013M_o} \quad (A2)$$

and

p_s = 0.1 atm:

$$(q_w)_s \sqrt{\frac{R_n}{p_s}} = (30.8 + 1.255M_o) \left(\frac{u_\infty}{10^4} \right)^{2.69 - 0.0134M_o} \quad (A3)$$

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